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Double Quantum Wire Magnetic Response

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ABSTRACT

The induced magnetic moment of a biased semiconductor tunnel-coupled parallel double quantum wire system is examined here. The wires are in a series arrangement with tunnel coupling to each other and to leads. Their parallel lengths and associated continuous spectrum are taken in the direction perpendicular to the lead-to-lead current. The equations of motion for the double-wire electron Green's function are formulated and analyzed using the transfer-tunneling Hamiltonian formalism. We determine the average magnetic moment of the double-wire system induced by a magnetic field applied perpendicular to the plane of the structure and we show that there are crossovers between diamagnetic and paramagnetic behavior, depending on the bias voltage, equilibrium chemical potential of the leads and temperature.

INTRODUCTION

There has recently been intensified interest in *extended* tunnel-coupled structures, in particular, parallel quantum wires [1-3], which have symmetric and antisymmetric states analogous to those of quantum dots [4,5]. Such double-quantum-wire systems have been fabricated by split-gate methods [6] or by cleaved edge overgrowth [7].

The double-wire system that we examine in regard to magnetic moment is illustrated in Fig.1. It consists of two tunnel-coupled parallel quantum wires of finite length L with wire separation $2d$ placed between two metallic leads. There is electron confinement in two dimensions (y and z) in both wires, and the energy spectrum in the third direction (x) is taken to be continuous. Subject to the bias voltage, electrons tunnel sequentially from the left lead to the left wire, tunnel from the left wire to the right wire, and, finally, tunnel from the right wire to the right lead. We assume that tunneling from wire to wire is much faster than tunneling from the leads to wires, because the potential barriers between leads and wires are higher than the barrier between the wires themselves. We neglect the Coulomb interaction between electrons. A magnetic field is

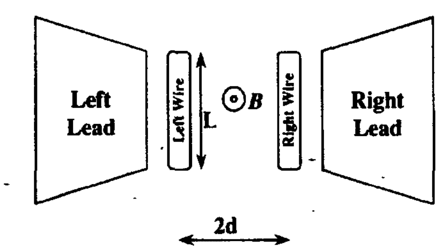


Figure 1. Schematic of the double-wire system.

taken to be applied perpendicular to the plane of this structure, facilitating the analysis of magnetic properties of the system. With the use of the nonequilibrium Green's functions, we analyze the magnetic moment of the double-wire system.

GREEN'S FUNCTION FORMULATION FOR DOUBLE-WIRE SYSTEM

The electron field operators in the left and right wires are described as

$$\hat{\Psi}_L(\boldsymbol{r},t) = \psi_L(y)\psi_0(z)\hat{\psi}_L(x,t), \tag{1}$$

$$\hat{\Psi}_R(\boldsymbol{r},t) = \psi_R(y)\psi_0(z)\hat{\psi}_R(x,t), \tag{2}$$

where $\psi_L(y)=\psi_0(y+d)$, $\psi_R(y)=\psi_0(y-d)$, ψ_0 is the ground state wave function for the y and z directions, and $\hat{\psi}_L(x,t)$, $\hat{\psi}_R(x,t)$ are the electron field annihilation operators for states of the x direction. The magnetic field, applied along the z-axis is taken in the gauge $\boldsymbol{A} = (-By,0,0)$. In this description, the second quantized double-wire Hamiltonian can be written in terms of an x-integral alone, using a δ-function confinement in the y direction to represent the narrow spatial extent of $|\psi_0(y)|^2$, as

$$\hat{H}_{DW} = \int dx\left(\hat{\psi}_L^+(x,t)\frac{(p_x - eBd/c)^2}{2m}\hat{\psi}_L(x,t) + \hat{\psi}_R^+(x,t)\frac{(p_x + eBd/c)^2}{2m}\hat{\psi}_R(x,t)\right)$$
$$-\Delta\int dx\left(\hat{\psi}_L^+(x,t)\hat{\psi}_R(x,t) + \hat{\psi}_R^+(x,t)\hat{\psi}_L(x,t)\right), \tag{3}$$

where $-\Delta$ is the tunneling constant. The retarded, advanced and lesser Green's functions describing x-propagation of the electrons in the double-wire system are defined as

$$G_{\alpha\beta}^r(x,t;x',t') = -i\left\langle\left[\hat{\psi}_\alpha(x,t), \psi_\beta^+(x',t')\right]_+\right\rangle\Theta(t-t'), \tag{4}$$

$$G_{\alpha\beta}^a(x,t;x',t') = i\left\langle\left[\hat{\psi}_\alpha^+(x',t'), \psi_\beta(x,t)\right]_+\right\rangle\Theta(t'-t), \tag{5}$$

and

$$G_{\alpha\beta}^<(x,t;x',t') = i\left\langle\hat{\psi}_\alpha^+(x',t'), \psi_\beta(x,t)\right\rangle, \tag{6}$$

where $\alpha,\beta=L,R$, $[\ldots,\ldots]_+$ is an anticommutator, and $\Theta(\tau)$ is the Heaviside unit step function.

The coupling of the double-wire system to the leads is described by the Hamiltonian

$$\hat{H}_{L\text{-}DW} = \sum_\alpha\int dx\left(\hat{\psi}_\alpha^+(x,t)C_\alpha(x,t) + C_\alpha^+(x,t)\hat{\psi}_\alpha(x,t)\right), \tag{7}$$

where

$$C_\alpha(x,t) = \int dydz\int d^3\boldsymbol{r}'\psi_0^*(z)\psi_\alpha^*(y)V_\alpha(\boldsymbol{r}-\boldsymbol{r}')c_\alpha(\boldsymbol{r}',t) \tag{8}$$

with $\alpha=L,R$ for left, right and c_α^+, c_α are the creation, annihilation operators of electrons in the α-lead and $V_\alpha(\boldsymbol{r}\text{-}\boldsymbol{r}')$ is the lead-wire coupling strength.

The leads are taken to be three-dimensional with Hamiltonian,

$$\hat{H}_{Ld} = \sum_\alpha\int d^3r c_\alpha^+(\boldsymbol{r},t)E_\alpha(\boldsymbol{p})c_\alpha(\boldsymbol{r},t), \tag{9}$$

having continuous spectrum in all three dimensions. The retarded and lesser Green's functions for the electrons in the leads (incorporating the lead-double-wire coupling strength) are given by

$$\operatorname{Im} g_\alpha^r(E,p_x) = -\frac{1}{2}\Gamma_\alpha(E,p_x) \tag{10}$$

and

$$g_a^<(E,p_x) = if_a(E)\Gamma_a(E.p_x), \tag{11}$$

where $f_a(E)$ is the Fermi function,

$$f_a(E) = \frac{1}{\exp\left(\frac{E-\xi_a}{T}\right)+1}, \tag{12}$$

$\xi_L = \xi + eU/2$, $\xi_R = \xi - eU/2$, ξ is the equilibrium chemical potential common to both leads. U is the applied bias voltage, and the lead-double-wire coupling constants $\Gamma_a(E,p_x)$ are defined as

$$\Gamma_a(E,p_x) = 2\pi\int\frac{dp_y}{2\pi\hbar}\frac{dp_z}{2\pi\hbar}|\psi_a(p_y)|^2|\psi_0(p_z)|^2|V_a(p)|^2\delta(E-E_a(p)). \tag{13}$$

The energy origin is taken as the ground state energy of the wire confinement potential.

The average magnetic moment induced by the applied magnetic field may be written in terms of electron Green's functions of the double-wire structure as

$$\langle\mu_z\rangle = -\frac{\partial\langle H\rangle}{\partial B} = -i\frac{edL}{mc}\int\frac{dp_x}{2\pi\hbar}\int\frac{dE}{2\pi\hbar}\Big(p_x\big(G_{LL}^<(E,p_x) - G_{RR}^<(E,p_x)\big) - \frac{eBd}{c}\big(G_{LL}^<(E,p_x) + G_{RR}^<(E,p_x)\big)\Big). \tag{14}$$

MAGNETIC MOMENT OF THE QUANTUM DOUBLE WIRE SYSTEM

The equations of motion for the double-wire electron Green's functions (Eqs.(4-6)) imply that there are two subbands in the double-wire region associated with bonding and antibonding states. The bonding subband energy is given by

$$E_B(p_x) = \frac{p_x^2}{2m} + \frac{m\omega_c^2 d^2}{2} - \sqrt{\Delta^2 + \omega_c^2 p_x^2 d^2}, \tag{15}$$

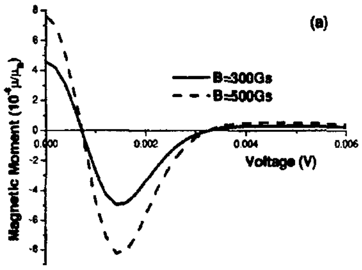
and the energy in the antibonding subband is given by

$$E_B(p_x) = \frac{p_x^2}{2m} + \frac{m\omega_c^2 d^2}{2} + \sqrt{\Delta^2 + \omega_c^2 p_x^2 d^2}, \tag{16}$$

where $\omega_c = eB/mc$ is the cyclotron frequency. We use these solutions in the determination of the average magnetic moment of the double-wire system. In the wide-band limit [8] of a symmetric structure, in which the coupling constants are essentially the same for both leads and are energy-independent, the induced magnetic moment in the double-wire system is found to be

$$\langle\mu_z\rangle = -\frac{ed^2L}{2c}\omega_c\int_{-\infty}^{\infty}\frac{dp_x}{2\pi\hbar}\left[\left(1+\frac{p_x^2}{m\Omega_p}\right)\left[f_L(E_A(p_x)) + f_R(E_A(p_x))\right] + \left(1-\frac{p_x^2}{m\Omega_p}\right)\left[f_L(E_B(p_x)) + f_R(E_B(p_x))\right]\right]. \tag{17}$$

It is evident from Eq.(17) that the contribution of the antibonding subband to the magnetic moment (first term in the large square brackets) is always diamagnetic, while the contribution of the bonding subband (second term) is diamagnetic for the part of the subband involving small momenta $(p_x^2 < m\Omega_p)$ and it is paramagnetic otherwise. This conclusion may also be obtained



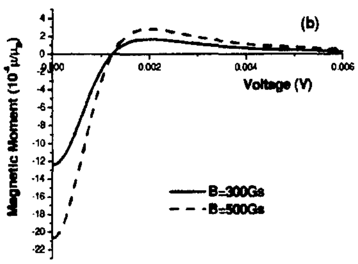


Figure 2. Bias dependence of the magnetic moment for two magnetic field strength, B=300 Gs (solid line) and B=500 Gs (dashed line) and for two equilibrium chemical potential of the leads, (a) ξ=525μeV and (b) ξ=-100μeV; μ_B is the Bohr magneton.

by taking derivatives of the subband energies (Eqs.(15,16)) with respect to the applied magnetic field. This derivative is always positive for the antibonding state, but it involves both positive and negative terms for the bonding state.

Figure 2(a,b) illustrates the bias dependence of the average magnetic moment for two magnetic field strengths, for two equilibrium chemical potentials of the leads, ξ=525μeV and ξ=-100μeV, and for the following parameters associated with a GaAs structure in our calculations: $\Delta = 75$ μeV; $\hbar\Gamma = 7.5$ μeV; $T = 3K$; $2d = 60nm$; $L = 10$ μm and $m = 0.067m_0$, where m_0 is the free electron mass. The magnetic moment is normalized to the Bohr magneton, $\mu_B = \hbar e/2m_0c = 9.27\cdot10^{-21}$ erg/Gs. One can see that the response of the system with equilibrium chemical potential of the leads ξ=525μeV, is paramagnetic in equilibrium, and it becomes diamagnetic with increasing bias, returning to paramagnetic at high bias. For the system with equilibrium chemical potential of the leads ξ=-100μeV, the equilibrium response is diamagnetic and there is only one crossover to paramagnetic behavior with increasing bias. It should be noted that, although the absolute values of the induced magnetic moment are different for different applied magnetic field strengths, the critical voltages for crossover between diamagnetic and paramagnetic response remain the same.

To achieve a better understanding of the magnetic response of the double-wire system and its bias dependence, we examined the dependence of the induced magnetic moment on the equilibrium chemical potential of the leads without bias, with the result shown in Figure 3(a); and with an applied bias, $U = 5\cdot10^{-4}$ V, as shown in Figure 3(b) for temperature $T = 1K$. The distribution functions of both leads are the same at zero bias and so are their contributions to the magnetic moment (Eq.(17)). Only the bottom of the bonding subband is populated for low values of ξ and T and the magnetic response is diamagnetic. The subband population increases with increasing ξ and, initially, the diamagnetic response increases when there are only electrons with low p_x-values. As electrons with larger p_x-values start to contribute, they compensate the contribution of the low-p_x electrons (the first inverted peak (negative) in Figure 3(a)) and the response even becomes paramagnetic when large-p_x electrons dominate. The antibonding subband is reached as ξ further increases, and its diamagnetic contribution leads to the second (positive) peak in Figure 3(a). The imposition of a finite bias differentiates the contributions of

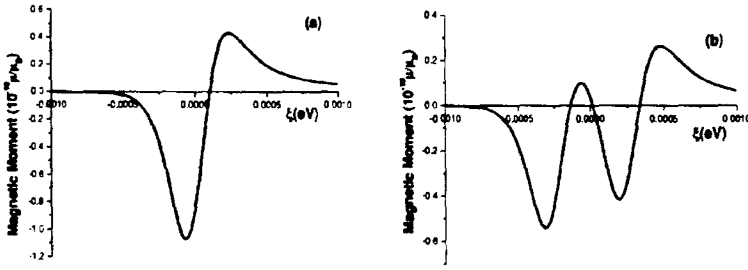


Figure 3. Induced magnetic moment as a function of equilibrium chemical potential of the leads for (a) zero bias, (b) $U = 5 \cdot 10^{-4}\ V$.

the left and right leads, shifting the functional dependence of Figure 3(a) in opposite directions by $\pm U/2$, respectively. Taken together, they yield the induced magnetic moment as a function of the equilibrium chemical potential of the leads, shown in Figure 3(b). Increasing the bias shift between the left and right leads (with their equilibrium chemical potential fixed) results in the induced magnetic moment shown as a function of bias voltage in Figure 2. In regard to its specific shape, the bias dependence of the induced magnetic moment and, in particular, its sign at zero bias and critical voltages, are determined by the common equilibrium chemical potential of the leads. It is evident from Figure 3(a) that the equilibrium magnetic response is paramagnetic for ξ=525μeV (see Figure 2(a)), whereas it is diamagnetic for ξ=-100μeV (see Figure 2(b)).

Higher temperatures smooth the distribution function of the leads and the peaks become less pronounced. The temperature dependencies of the induced magnetic moment are presented in Figure 4 for magnetic field strength 300Gs, for two values of equilibrium chemical potential of the leads and for two applied bias voltages. One can see that the induced magnetic moment decreases with increasing temperature and in this situation the effect of applied voltage also tends to vanish.

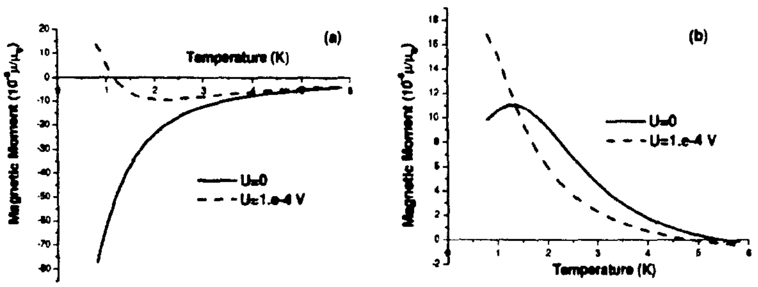


Figure 4. Temperature dependence of the induced magnetic moment for zero bias (solid lines) and $U = 5 \cdot 10^{-4}\ V$ (dashed lines) and for two equilibrium chemical potential of the leads, (a) ξ=-100μeV and (b) ξ=525μeV.

CONCLUSIONS

Our analysis of a biased tunnel-coupled double-quantum-wire system (connected to leads in a series arrangement, with a magnetic field normal to the plane of the wires) has led to the determination of the induced magnetic moment as a function of bias voltage, equilibrium chemical potential of the leads, and temperature. In this, we demonstrated that, at low temperatures, there are crossovers between diamagnetic and paramagnetic behavior with increasing bias voltage. These properties of the double-wire structure introduce a mechanism for the lead-to-lead bias control of the induced magnetic moment of this system.

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